

# Higgs Couplings after the Discovery

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Following the ATLAS and CMS analyses presented around ICHEP 2012 we determine the individual Higgs couplings. The new data allow us to specifically test the effective coupling to photons. We find no significant deviation from the Standard Model in any of the Higgs couplings.

A resonance peak consistent with a scalar Higgs boson [1] has been discovered by ATLAS [2] and CMS [3]. It completes the Standard Model of elementary particles and establishes the fundamental concept of gauge theories.

In its Standard Model form the Higgs boson couples to all particles proportional to their masses [4–6]. Beyond the Standard Model, Higgs analyses probe new physics orthogonally to direct searches [7]. Induced dimension-five couplings to gluons and to photons are among the key parameters for Higgs analyses at the LHC. In addition, new physics can couple to the Higgs sector via renormalizable dimension-four operators [8]. Similarly, strongly interacting models will alter all Higgs couplings in a way which reflects the underlying theory [9–15].

SFITTER Higgs analyses — the general Higgs coupling analysis and its first application on data is comprehensively documented in Refs. [9, 10, 16]. \* All tree-level Higgs couplings and their ratios are parameterized as

$$g_{xxH} \equiv g_x = (1 + \Delta_x) g_x^{\text{SM}}$$

$$\frac{g_{xxH}}{g_{yyH}} \equiv \frac{g_x}{g_y} = (1 + \Delta_{x/y}) \left( \frac{g_x}{g_y} \right)^{\text{SM}}. \quad (1)$$

For the loop-induced Higgs-photon coupling this means

$$g_{\gamma\gamma H} \equiv g_\gamma = (1 + \Delta_\gamma^{\text{SM}} + \Delta_\gamma) g_\gamma^{\text{SM}}. \quad (2)$$

The Standard Model value is given by the bottom, top, and  $W$  loops.  $\Delta_\gamma^{\text{SM}}$  contains the measured direct couplings to all Standard Model particles,  $\Delta_\gamma$  parameterizes additional contributions to the effective vertex.

All underlying operators we assume to be Standard-Model like. A dedicated analysis of the ‘Higgs’ quantum numbers requires a detailed study of angular correlations in  $H \rightarrow ZZ$  decays [17] or weak boson fusion Higgs production [18].

The Higgs width cannot be measured independently at the LHC, but it enters every observable event rate as an over-all normalization. We consistently assume [19]

$$\Gamma_{\text{tot}} = \sum_{\text{obs}} \Gamma_x(g_x) + 2\text{nd generation} < 2 \text{ GeV}. \quad (3)$$

At the LHC we cannot observe  $g_c$ . To avoid systematic offsets in our results we link all second-generation Yukawa couplings to their third-generation counter parts, e.g.  $g_c = m_c/m_t \times g_t^{\text{SM}}(1 + \Delta_t)$ .

Experimental and theoretical uncertainties [20–22] enter our fit including full correlations. Theoretical uncertainties we include in the centrally flat RFIT scheme [23]. All background rates, efficiencies and experimental uncertainties are extracted from ATLAS and CMS publications [2, 3]. Based on all this we compute an exclusive log-likelihood map of the Higgs parameter space. Individual distributions are defined through a profile likelihood. The best-fitting points we identify using Cooling Markov Chains [10] combined with MINUIT, their 68% confidence intervals require 5000 toy measurements.

Global picture — the analysis of the 7 TeV and 8 TeV Higgs channels closely follows Ref. [9]. In this update we include all recently published ATLAS [2] and CMS [3] analyses, including the recent  $H \rightarrow WW$  ATLAS results.

Before we show the measured individual Higgs couplings we briefly discuss the global structure of the log-likelihood map, focusing on correlations. Because we now allow for an independent  $g_\gamma$  variation we are most interested in the correlation between the Higgs couplings to top quarks and to  $W$ -bosons.

In the left panel of Fig. 1 we see the expected correlation of these two couplings in the absence of an additional parameter  $\Delta_\gamma$ . This log-likelihood map is based on the proper errors of the 2011 and 2012 analyses, but assuming Standard Model central values. Two solutions arise from a sign change in the top Yukawa coupling,  $\Delta_t \sim -2$ . Only  $g_W$  we keep positive without loss of generality. The preference for positive  $g_t$  indicates that the degeneracy of the two solutions is broken by the amplitude-level interference between the top and  $W$  loops in the effective  $g_\gamma$  computation.

In the right panel of Fig. 1 we show the same distribution based on data. The two expected solutions indeed appear, but a third scenario features around  $\Delta_W \sim -1$  and  $\Delta_t \sim 1.5$ . In this case the  $W$ -boson decouples from the Higgs, as it is still allowed within errors. The usually smaller top loop now induces the effective vertex on its own, requiring a slightly enhanced Yukawa coupling.

In contrast to the earlier analysis of Ref. [9] we do not attempt to constrain the parameter space to Standard-Model like solutions. This means that secondary solutions will appear with a competitive quality of fit. For

\* Continuous Updates of some figures in this letter can be found under [www.thphys.uni-heidelberg.de/~plehn](http://www.thphys.uni-heidelberg.de/~plehn)

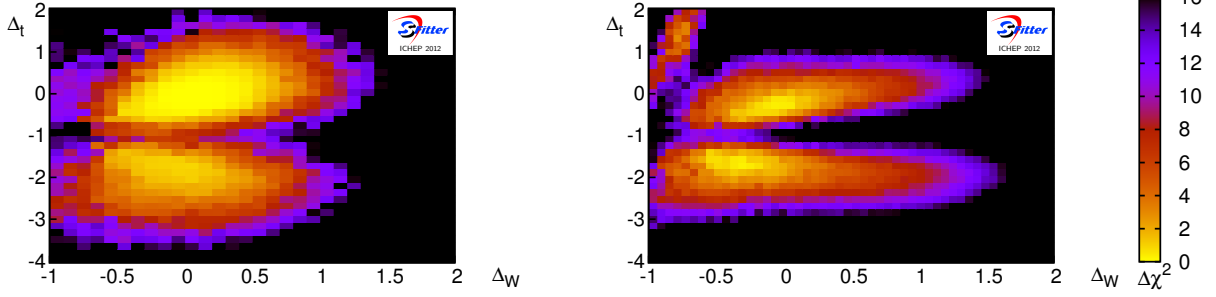


Figure 1:  $\Delta_W$  vs  $\Delta_t$  for the expected SM measurements (left) and the actual measurements (right), assuming  $m_H = 126$  GeV.

example, including all Standard Model Higgs couplings, but no free coupling to photons we find three equally likely points:

$\Delta_W$	$\Delta_Z$	$\Delta_t$	$\Delta_b$	$\Delta_\tau$	$\chi^2/\text{d.o.f.}$
-0.03	-0.02	-0.25	-0.25	-0.90	27.7/49
-0.05	-0.04	-0.34	-1.73	-0.70	27.6/49
-0.29	-0.09	-1.65	-0.32	-0.70	27.7/49

In the second and third line the bottom and top Yukawa coupling, respectively, have changed sign. As expected, we cannot distinguish such alternative scenarios with the current data.

Local picture — from the exclusive log-likelihood maps we can extract individual Higgs couplings. We are directly sensitive to  $\Delta_{W,Z,\tau}$  and can extract  $\Delta_t$  from the effective photon and gluon couplings as well as  $\Delta_b$  from the total width. As we will see below, we can even constrain an additional free parameter  $\Delta_\gamma$ .

Of course, extracting any smaller number of model parameters is technically easier and will lead to smaller error bars. For example, we can test a hypothetical universal form factor of all tree-level Higgs couplings,

$$\Delta_x \equiv \Delta_H \quad \text{for all } x. \quad (4)$$

In Fig. 2 we show the expected and observed central value and error bar on this form factor. Such a form factor is barely consistent with the Standard Model value  $\Delta_H = 0$ . Its low central value is a result of all three third-generation Yukawa couplings tending towards smaller values. Quoting this result we need to keep in mind that it is only sensible if all individual  $\Delta_x$  are consistent.

Two-parameter fits, on the gauge coupling side, are motivated by electroweak precision data. In the absence of new physics signals these measurements point towards  $\Delta_W = \Delta_Z$ . We define

$$\begin{aligned} \Delta_W &= \Delta_Z \equiv \Delta_V \\ \Delta_b &= \Delta_t = \Delta_\tau \equiv \Delta_f. \end{aligned} \quad (5)$$

While the vector boson coupling in Fig. 2 is measured in complete agreement with the Standard Model the Yukawa couplings have consistently low best-fit values. However, within the uncertainties this is no problem.

Obviously, what we really want to extract (if possible) is the set of all couplings individually. Figure 2 shows the central coupling values for  $W$  and  $Z$ -bosons as well as the third-generation fermions.

Comparing the expected to the observed uncertainties we see that the two massive gauge couplings are extracted very well after including the 8 TeV data. The indirectly measured top and bottom Yukawa couplings come out slightly low, but agree with the Standard Model expectations within relatively large error bars. Those are due to their indirect determination. A tau Yukawa coupling is not experimentally established yet. For example comparing the measured value of  $\Delta_b$  with the ratio  $\Delta_b/W$  we see no significant improvement. The ATLAS and CMS measurements are still largely statistics limited, so forming ratios does not help.

As widely discussed in the literature, the observed number of Higgs events decaying to photons is slightly larger than the Standard Model expectation. In Fig. 2 we see that without a free Higgs coupling to photons the best fit resides around  $\Delta_W \sim 0$ . The central point for the top Yukawa is  $\Delta_t \sim -0.25$ , enhancing the Higgs branching ratio to photons, but reducing the production cross section from gluon fusion. However, the central value

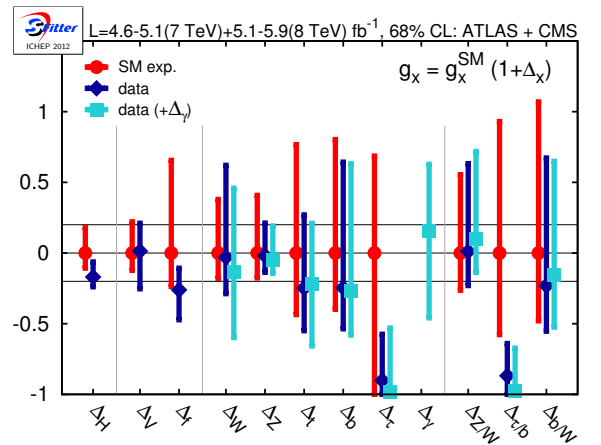


Figure 2: Results based on 2011 and 2012 data, for the SM signal expectation and for the data ( $m_H = 126$  GeV). We also show the form factor result  $\Delta_H$  and universal fermion and boson couplings  $\Delta_{V,f}$ . The band indicates a  $\pm 20\%$  variation.

of  $\Delta_b$  is half a standard deviation below the Standard Model expectation, corresponding to a slightly increased number of Higgs events in the two-photon channel.

Free Higgs-photon coupling — finally, in Fig. 2 we show the fit to all Standard Model couplings plus a free shift in the higher-dimensional photon-Higgs coupling. The  $\Delta_W$  measurement now mainly relies on the observed  $H \rightarrow WW$  decays, without the additional information from the photon decay mode; its central value moves down by 13%, well within its uncertainty. The top Yukawa is still extracted from the Higgs coupling to gluons and comes out slightly low. Similarly, the bottom Yukawa contributing to the total width is 25% below the Standard Model expectation. These two effects from the Yukawa coupling roughly cancel each other, but the reduced value of  $\Delta_W$  is compensated by the effective Higgs-photon coupling. Note that all shifts are within one standard deviation for the respective couplings. For this additional higher-dimensional coupling as defined in Eq.(2) we find

$$\Delta_\gamma = 0.16 + 0.47 - 0.61 \quad (68\% \text{ CL}) . \quad (6)$$

For a switched sign of  $g_t$ , which yields the same log-likelihood value, this central value moves to  $\Delta_\gamma = -0.22$ . Hence, we find no evidence for an enhanced Higgs coupling to photons; this is in apparent conflict with the

ATLAS and CMS results. The reason is that we consistently use the best-fit values for all other couplings ( $1 + \Delta_\gamma^{\text{SM}}$ ) in the comparison between theory and experiment for the  $H \rightarrow \gamma\gamma$  channels, while ATLAS and CMS use the Standard Model input.

Starting from Fig. 2 we see the next steps: improved statistics in the weak-boson-fusion channel will improve the  $g_\tau$  measurement [24]. To be able to test the induced Higgs-gluon coupling we need a direct determination of the top Yukawa coupling in  $t\bar{t}H$  production. Similarly, to probe contributions to the Higgs width a direct measurement of the bottom Yukawa coupling is mandatory. Both will hugely benefit from Higgs and top tagging analyses [25].

Outlook — in this updated Higgs coupling analysis following Ref. [9] we show that all ATLAS and CMS Higgs measurements are unfortunately well explained by a Standard Model Higgs boson. In addition to some toy models we determine all Standard Model Higgs couplings individually, including an independent Higgs coupling to photons. None of the measured couplings deviates from its Standard Model values significantly.

Acknowledgments — we would like to thank Dirk Zerwas, Markus Klute, and Remi Lafaye for an absolutely great collaboration on SFITTER-HIGGS.

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